Improving CQS, CRI and LO of the 5600K RP-WLEDs by Red-emitting Conversion Phosphor

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Abstract: In the few last decades, Light-emitting diodes (LEDs) is considered the newest solid-state lighting technique advancement in both industry and civil lighting. In this paper, we improve the Color rendering index (CRI), Color quality scale (CQS) and lumen output (LO) of the 5600 K remote-packaging white LEDs (RP-WLEDs) by the red-emitting conversion Sr₂Si₅N₈:Eu²⁺ phosphor. The influence of the red phosphor concentration on the CQS, CRI, and LO are proposed and demonstrated by using Mie Theory with Mat Lab and Light Tools software. The results draw that CRI, CQS, and LO are significantly affected by the red phosphor concentration, which can provide a potential practical recommendation for manufacturing RP-WLEDs.

Keywords: RP- WLEDs; CRI; CQS; LO

Introduction

In the few last decades, Light-emitting diodes (LEDs) is considered as the newest solid-state lighting technique advancement in both industry and civil lighting [1–3]. This is based on the following advantages of LEDs such as 1) high energy saving, 2) long lifetime (over 50,000 hours or more), 3) environment-friendly characteristics, 4) wide range color temperatures (4500 K–12,000 K), 5) wide operation temperature (~20 °C to 85 °C), and 6) quick startup. Based on these, LEDs have been considered as the fourth generation of light sources in our time [1-4].

In the commonly, LEDs manufacturing process divides into three stages such as the upstream, the midstream, and the downstream. The emitting layer, buffer layer, cladding layer, and reflector are related to the upstream stage, phosphor packaging and packaging are the midstream stage. Finally, the product application in general and civil purposes are related to the downstream stage. In the midstream LEDs industry, the packaging process plays an important role in converting the blue light from the blue LEDs chip into white light. Packaging not only can ensure better performance of LEDs devices by enhancing reliability and optical characteristics but can also realize control and adjustment of the final optical performance [4-7]. From this analysis, improving and enhancing the optical properties (in term of color quality scale CQS, Color rendering index CRI and lumen output LO) of W-LEDs by controlling the packaging process is focused by many studies. Such as, the optical properties of LEDs are enhanced by controlling the packaging structures and phosphor materials as shown in [9]. Furthermore, by adding phosphors Sr₁₋ₓBaxSi₅N₈:Eu²⁺, Sm³⁺ [11], or by adding Sr₂Si₅N₈:Eu²⁺ [12,13] to the phosphor layer of LEDs the optical properties are improved significantly.
In this paper, we improve the Color rendering index (CRI), Color quality scale (CQS) and lumen output (LO) of the 5600K remote-packaging white LEDs (RP-WLEDs) by the red-emitting Sr$_2$Si$_5$N$_8$:Eu$^{2+}$ phosphor. The influence of the red phosphor concentration on the CQS, CRI, and LO is proposed and demonstrated by using Mie Theory with Mat Lab and Light Tools software. The results draw that CRI, CQS, and LO are significantly affected by the red phosphor concentration, which can provide a potential practical recommendation for manufacturing RP-WLEDs.

The end of this paper can introduce by the following stages. The physical model of RP-WLEDs is proposed by Light Tools, and the mathematical description is calculated by Mat Lab in section 2. Furthermore, the simulation results are analyzed and demonstrated in section 3. Finally, some conclusions are drawn from the results in section 4.

**Research Method**

We simulate the 5600 K RP-WLEDs in the Light Tools software based on the Monte Carlo ray-tracing method. The physical model of RP-WLEDs is shown in Fig. 1. In the simulation model of 5600 K RP-WLEDs, the main parameters of the RP-WLEDs are assumed as bellows:

1) The reflector: 8 mm bottom length, 2.07 mm height, and 9.85 mm length.
2) The thickness of the remote phosphor layer is 0.08 mm.
3) The LEDs chip: 1.14 mm square base and 0.15 mm height.

The radiant flux of each blue chip is 1.16 W at wavelength 455 nm [12,13].

![Fig. 1. The RP-WLEDs physical structure in Light Tools 8.4 software.](image)

For investigating the effect of the concentration of red phosphor on CRI, CQS, and LO of RP-WLEDs, we change the concentration of the red phosphor from 6% to 24%. The refractive index of the red and yellow phosphors are fixed as in many previous studies at 1.80 and 1.83, respectively. The average radius of the phosphor particles are 4 μm and the refractive index of the silicone glue was chosen 1.5 [12,13]. The diffusional particle density is varied to fix the average correlated color temperature (CCT) value of RP-WLEDs at 5600 K.

Applying Mie theory [14-17], the scattering coefficient $\mu_{\text{ sca}}(\lambda)$, anisotropy factor $g(\lambda)$, and reduced scattering coefficient $\delta_{\text{ sca}}(\lambda)$ can be computed by the below expressions:

$$\mu_{\text{ sca}}(\lambda) = \int (N(r)C_{\text{ sca}}(\lambda,r)dr$$

$$g(\lambda) = 2\pi \int \int p(\theta,\lambda,r)f(r)\cos\theta d\theta d\lambda$$

$$\delta_{\text{ sca}} = \mu_{\text{ sca}}(1-g)$$

Where $N(r)$ is the distribution density of diffusional particles (mm$^3$), $C_{\text{ sca}}$ is the scattering cross sections (mm$^2$), $p(\theta,\lambda,r)$ is the phase function, $\lambda$ is the light wavelength (nm), $r$ is the radius of diffusional particles (μm), $\theta$ is the scattering angle (°), and $f(r)$ is the size distribution function of the diffuser in the phosphorous layer.

Furthermore, the relationship between luminous output and the red phosphor concentration can be formulated according to Mie-scattering theory and the Beer-Lambert law [14-17] as the following

$$I = I_0 \exp(-\mu_{\text{ ext}}L)$$

Where $I$ is the transmitted light power, $I_0$ is the incident light power, $\mu_{\text{ ext}}$ is the extinction coefficient, $L$ is the path length, and $N$ is the number of particles per cubic millimeter.

According to Mie-scattering theory, the extinction cross section $C_{\text{ ext}}$ of phosphor particles can be characterized by the following equation:

$$C_{\text{ ext}} = \frac{2\pi a^2}{x^2} \sum_{n=1}^{\infty} (2n+1)\Re(a_n + b_n)$$

Here, $x = 2\pi a/\lambda$ is the size parameter; $a_n$ and $b_n$ are the expansion coefficients with even symmetry and odd symmetry, respectively.

**Results and Discussion**

As displayed in Fig. 2, the scattering coefficients increase in the trend red-emitting Sr$_2$Si$_5$N$_8$:Eu$^{2+}$ phosphor concentration from 6% to 24%. It is observed that the white-light quality can be improved by varying red-emitting Sr$_2$Si$_5$N$_8$:Eu$^{2+}$ phosphor concentration. The
scattering effects of red-emitting Sr$_2$Si$_5$N$_8$:Eu$^{2+}$ particles remarkably affect on RP-WLEDs. This based on the fact that the red phosphor has a higher absorption ability for the blue light from LEDs chip. Therefore, the domination of emitted red light could be done for compensating red light in RP-WLEDs.

The reduced scattering coefficient of red-emitting Sr$_2$Si$_5$N$_8$:Eu$^{2+}$ with wavelengths 453nm, 555nm and 680nm are the same with each other as shown in Fig 3. It indicated that the scattering stability of red-emitting Sr$_2$Si$_5$N$_8$:Eu$^{2+}$ is useful for controlling the color properties of RP-WLEDs.

By using Light Tools and varying concentration red-emitting Sr$_2$Si$_5$N$_8$:Eu$^{2+}$ phosphor from 6% to 24%, the CQS of the 5600K RP-WLEDs are drawn in Fig. 4. From the results, we can see that the CQS changes from 63 to 67 when we vary the concentration of the red phosphor from 6 % to 24 %. After that, Fig. 5 plots the influence of particle concentration on CRI. From these results, CRI remarkably increased while the concentration of red-emitting Sr$_2$Si$_5$N$_8$:Eu$^{2+}$ phosphor rose continuously from 6 % to 24 %.

The influence of the red-emitting phosphor concentration on the luminous efficacy of the 5600K RP-WLEDs is presented in Fig. 6. Fig. 6 showed that the luminous efficacy increased crucially while the concentration of red-emitting Sr$_2$Si$_5$N$_8$:Eu$^{2+}$ phosphor grown from 4 % to 20 %. After that, the lumen output had a massive decrease with 20 % to 24 % red-emitting Sr$_2$Si$_5$N$_8$:Eu$^{2+}$ phosphor. The highest value of the lumen output can reach 18 % to 20 % red-emitting Sr$_2$Si$_5$N$_8$:Eu$^{2+}$ phosphor.

Conclusion
From results and theory analysis, some conclusions are proposed:
1) CQS and CRI have huge increase with rising concentration of the red-emitting Sr$_2$Si$_5$N$_8$:Eu$^{2+}$ phosphor particles.

2) In the beginning, the lumen output had a considerable increase and then decrease in the end. The highest value of the lumen output can reach 18% to 20% Sr$_2$Si$_5$N$_8$:Eu$^{2+}$ phosphor.

References


